Mars Mission Science Operations Facilities Design[1]

Jeffrey S. Norris[*], Roxana Wales[α], Mark W. Powell[*], Paul G. Backes[*], Robert C. Steinke[*]
Jeffrey.S.Norris@jpl.nasa.gov, Rwales@mail.arc.nasa.gov, Mark.W.Powell@jpl.nasa.gov,
Paul.G.Backes@jpl.nasa.gov, Robert.C.Steinke@jpl.nasa.gov

[*]Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

[α]NASA Ames Research Center
Moffett Field, CA 94035

Abstract— A variety of designs for Mars rover and lander science operations centers are discussed in this paper, beginning with a brief description of the Pathfinder science operations facility and its strengths and limitations. Particular attention is then paid to lessons learned in the design and use of operations facilities for a series of mission-like field tests of the FIDO prototype Mars rover. These lessons are then applied to a proposed science operations facilities design for the 2003 Mars Exploration Rover (MER) mission. Issues discussed include equipment selection, facilities layout, collaborative interfaces, scalability, and dual-purpose environments. The paper concludes with a discussion of advanced concepts for future mission operations centers, including collaborative immersive interfaces and distributed operations. This paper's intended audience includes operations facility and situation room designers and the users of these environments.

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1. INTRODUCTION

Delivering a spacecraft safely to the surface of Mars for a few short months of operations requires millions of dollars and years of concerted effort by hundreds of people. Even when a spacecraft survives the difficult journey, its already brief lifespan may be abruptly ended at any time by the harsh Martian environment. While it is impossible to quantify the value of the vast knowledge that can be gained through a successful mission to Mars, a crude approximation of the "cost" of each day of operations can be arrived at by simply dividing the money spent on the mission by the number of days of surface operations. The budget of the 2003 Mars Exploration Rover (MER) mission is approximately 700 million dollars. Since this mission plans to operate two rovers on the surface of Mars for 90 sols each (where a "sol" is a Martian day), the price tag for a single day of MER operations is approximately 4 million dollars.

Figure 1: Scientists working in the 2001 FIDO field test operations center

When these stakes are considered, it is clear that every day that a spacecraft is operational on Mars must be used with the utmost efficiency. To achieve this goal, great care must be taken in the selection of the operations team, the development of the software they use, and the design of the facility they work in. This paper is focused on the last of these items.

Research has shown that there is a direct relationship between workplace design and productivity. [1] Furthermore, researchers have documented several interaction zones ranging from the "intimate distance" (less than 18 inches) to the "public distance" (greater than 12 feet). The facility designs outlined in the later sections of this paper attempt to keep the distance among group members within the so called "social distance") between 4 and 12 feet), which has been shown to facilitate productive interactions between people. [2]

With some very important exceptions and considerations, the amount of work that any team can accomplish can generally be increased through two means: increasing the time that the team is allowed to work and increasing the size of the team. Unfortunately, in the case of Mars mission

[1]0-7803-7231-X/01/$10.00/© 2002 IEEE

science operations, more time is typically not an option. The operations process for the MER mission, for instance, plans to use every minute that the rover is not operating to develop the commands for the next sol of operations, and only about 5 hours of this time is allotted for science operations. This problem is compounded by the fact that NASA's Mars missions are becoming more ambitious in terms of mission duration, science goals, and spacecraft complexity. Since time is not a flexible quantity in this domain, successful science operations are only accomplished through the combined efforts of a large number of scientists and engineers. As a side benefit, a large team allows the mission to staff experts in a wide variety of fields that may be useful during operations.

As anyone who has participated in a large project already knows, simply increasing the size of a team does not necessarily enable that team to accomplish more work. Among the quantities that must increase with team size in order to realize any improvement in performance is what will be referred to in this paper as the *effective capacity* of the operations facility.

We define the effective capacity of an operations facility as the number of people that it enables to be *meaningfully* engaged in the operations process. A person is meaningfully engaged if the following conditions are met:

1. They can comfortably see, hear, and communicate with everyone else in the group
2. They can see the material being discussed (typically data on a piece of paper, computer monitor, or projection screen)
3. They can provide input to the product being developed by the group.

The effective capacity of a facility is clearly far less then the number of people that can physically fit in the facility. For example, a typical office with a desktop computer has an effective capacity of around 4 people, while a small conference room with a projection screen has an effective capacity of around 10. The facility proposed in section 5 of this paper has an effective capacity of 100. Little or no benefit is accomplished when the effective capacity of an operations facility is exceeded. At best, operations staff will be underutilized and at worst, operations performance will actually degrade.

This paper discusses several operations facilities, beginning with a brief discussion of the facility used for the Pathfinder. This is followed by a more lengthy discussion of the lessons learned from a series of mission-like field tests of the FIDO prototype Mars rover. These lessons form the basis of a series of operations facility designs for the 2003 Mars Exploration Rover mission, and some advanced operations facilities concepts for missions beyond 2003. The effectiveness of these operations centers, when possible, is quantified in terms of effective capacity.

2. Facilities for Past Mars Missions

The Mars Pathfinder mission science operations center was constructed on a single floor of building 230 at JPL. Everyone interviewed commented that this "single-floor approach" greatly improved communication among the operations personnel. The two main rooms for science operations were the science work area (also affectionately called the "science playpen") and a large meeting room where science and engineering results and recommendations were presented daily. The science work area was a large (more than 1500 square feet) room without interior dividing walls. Computers were placed on tables along the outside edge of the room and in the center.

The mission science team was divided into a set of "Science Theme Groups" (STGs). Each STG represented a particular scientific interest, and was responsible for recommending activities pertinent to that interest. Sections of the science work area were set aside for each STG, with some common areas left unassigned. While it is difficult to perform a detailed analysis on an operations facility that doesn't exist anymore, interviews with members of the Pathfinder mission science team indicate that the effective capacity of the science work area was greatly exceeded. While it may seem that the somewhat ad-hoc room design with a lack of any division between the STG work areas would have allowed for increased communication between the groups, it unfortunately resulted in very noisy and chaotic environment. There was also very little use of technology to enable large groups of people to discuss data.

Each day, the mission science team left this work area at a prearranged time and met in a second room for a meeting. In this meeting, science and engineering results were presented, and recommendations were made to the sequencing team for the next day of activities. This two room approach (as opposed to holding the daily meeting in the science work area) was found to have some benefits. By using a second room for the daily meeting, much of the clutter of the science work area could be left behind. Since the second room was designed only as a meeting room and not as a place for collaborative work, it was straightforward to make its effective capacity very large (around 100 people). Furthermore, the use of a dedicated meeting room allowed the design of the science work area to focus on a more specific task.

However, as will be explained in several contexts below, using two rooms for the work area and meeting area has some drawbacks. If a single room can be designed that serves both purposes equally well, significant improvements can be realized in operations efficiency.

3. FIDO Field Test Operations Facilities

The FIDO prototype Mars rover was designed as a technology test and integration platform for the 2003 mission. [3] Until the mission test vehicles are constructed, it will be the closest thing to the rovers that will be launched in 2003. In addition to testing candidate technologies for the mission in an integrated environment, the FIDO rover has been the centerpiece of a series of highly successful field exercises intended to test advanced operations software, validate mission operations methods, and train the scientists that will be responsible for the operation of the 2003 mission. This discussion focuses on the facilities used for the three FIDO field tests that took place in 2001.

The participants in the field tests were members of the Athena Science Team, the group of scientists responsible for the instruments of the MER rovers. During operations, these scientists form the Science Operations Working Group (SOWG). The scientists were divided into three Science Theme Groups: Geology, Mineralogy, and Long Term Strategic Planning.

Facilities Equipment

The FIDO field test operations centers were all constructed in JPL's Planetary Robotics Lab (building 82). Space was limited- 30 scientists, 5 test administration staff, 15 operations engineers, and numerous visitors (around 50 people in all) had to fit in an area only 46 feet long and 30 feet wide along with numerous computers, projection equipment, and other materials.

Each STG was provided with seven chairs, two 5' x 2.5' tables, laser pointers, easels with large pads of paper, and places to post large printouts and maps. Each STG was also given a workstation with the WITS (Web Interface for Telescience) software, which they used to analyze acquired data and plan rover activities. The STGs had shared access to a black and white laser printer, a color laser printer, and a large format color plotter. Each STG area had power and network connections to allow the scientists to use their personal laptop computers during operations. Fortunately, building 82 has raised flooring, which allowed us to easily relocate these connections as we tried various layouts.

Three rear projection screens were set up at the far end of the room for the display of data for discussion by the whole SOWG. The projectors for these screens were driven by the Uplink Lead's computers. In past tests, standard front project screens were used, but rear projection provided a brighter picture and allowed the screens to be closer to the scientists. The screens were elevated about 5 feet above the floor, which allowed the whole room to comfortably see them.

Facilities Layout

A different facility layout was used for each test, with numerous comments collected at the end of each test to guide the construction of the next facility. The three layouts used are illustrated in figure 2.

The layout on the left side of figure 2 was used for the first test. The three STGs were placed side by side in front of the rear projection screens. The tables for the theme groups were arranged in a "T" shape, with enough space between the tables for two chairs. Since many of the scientists were learning the WITS tool during the ORT, groups were assigned an operator familiar with the tool who demonstrated and facilitated its use during the tests. It was expected that most of the theme group would congregate around the table without the WITS workstation, called the "discussion table" to develop plans for the next sol (a sol is one day on Mars). Then they would handover the plan to the theme group's WITS operator who would enter their decisions into the WITS workstation on the other table.

What actually occurred was that the scientists almost completely ignored the "discussion table" and crowded around the table with the WITS workstation. Rather than print out images and data and take them to the discussion table, the scientists immediately began to work collaboratively and directly from the WITS screen. The area in front of the screen, not the discussion table, became the area of main activity. Unfortunately, the orientation of the table only allowed a small number of people to sit near the workstation, leaving many people standing behind those seated for long periods of time. Despite the awkward arrangement, the scientists continued to work this way, motivated by their desire to quickly access the data and analyze it collaboratively within a shared workspace. They developed their work practice based on the situated nature of their activity, adapting previous expectations of how they would work (as identified by the layout of the tables) into a new work practice based on their current circumstances and needs. [4] The feedback received from the scientists on this layout was very negative. Complaints included being too "crowded", noise, and difficultly interacting within one STG and with other STGs. The effective capacity of this facility, analyzed after the fact, was approximately only 30 (recall that almost 50 people attended the test). Only 2-3 people from a STG could comfortably sit around the WITS workstation, and since most meaningful interaction occurred around this workstation, the effective capacity of each theme group area was exceeded by more than a factor of 2.

The layout in the middle of figure 2 was used for the second test, and sought to increase the effective capacity of each theme group area. By turning the workstation table 90 degrees and placing the monitor on one end of the table, 5 people could "crowd around" the WITS workstation.

The results from this new arrangement were mixed. More scientists were able to sit near the WITS workstation, but the second table for each theme group was again largely unused for the first day of the test. Again the scientists demonstrated that they wanted a larger shared activity space that included the WITS tool as the focus of discussion. To this end, on the second day, two theme groups decided to try their own arrangements of the tables, again with mixed results. The middle theme group (mineralogy) rotated their discussion table 90 degrees and placed the short end against the workstation table, resulting in a single, long table.

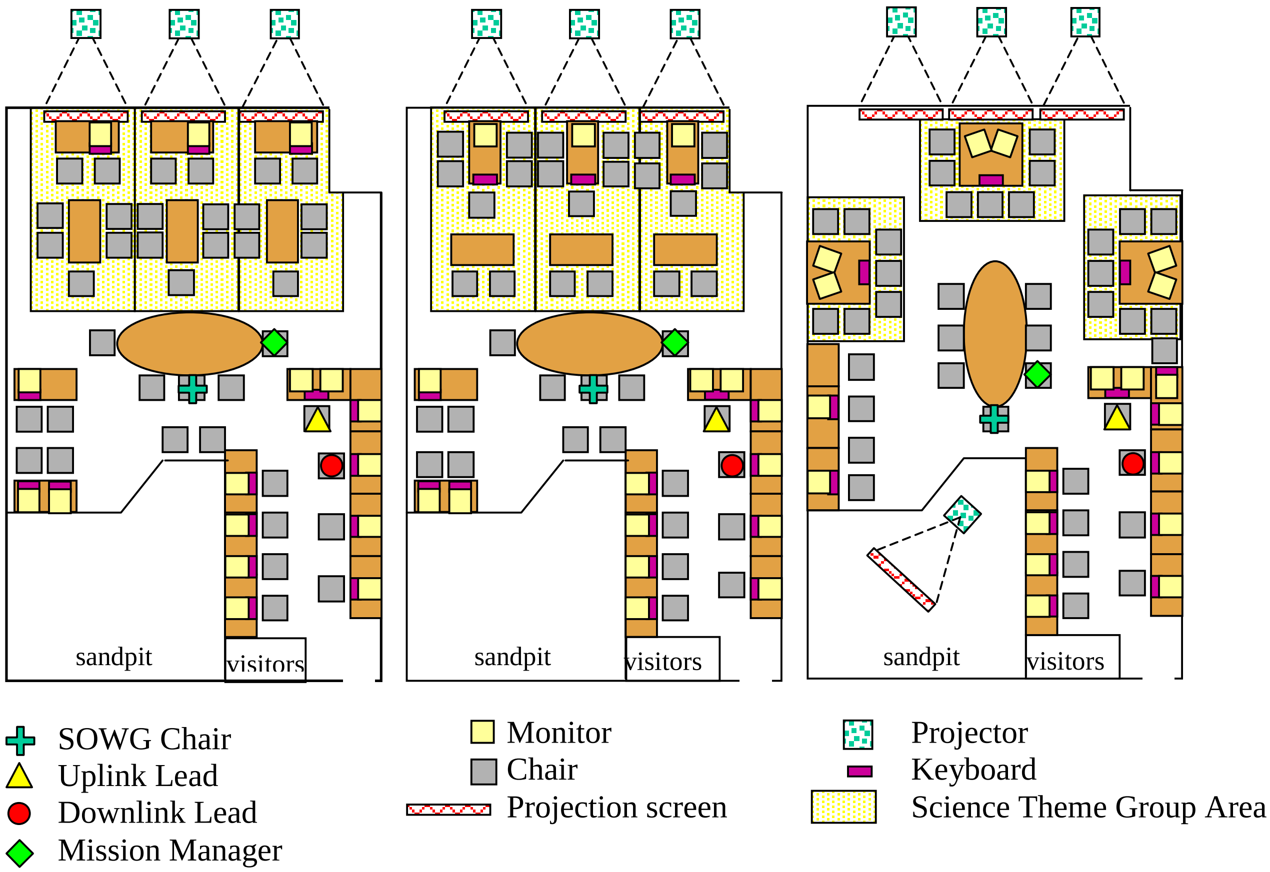

Figure 2: The three layouts used for the 2001 FIDO Field Tests

While this allowed all of the scientists to sit at a single table, we observed that it also made it difficult for the group to converse as a single group. Instead, the configuration broke up group activity and discussion into at least two or three distinct subgroups. In addition, the people on the far end of the elongated table opposite the WITS workstation were unable to see what was on the computer screen. This table arrangement did not increase the effective capacity of the theme group area. The left theme group (geology), on the other hand, kept the T formation but moved the tables together creating a closed vs. an open T formation. This arrangement made it easier for the group to hold discussions that included everyone at tables but the computer screen was still far away from people at the far end of the T. Based on our observations of the work practice of the two groups, we decided that a large square table might be a superior approach, creating a more open discussion area while simultaneously allowing more participants an easier view of the monitors. The final facilities layout sought to provide the square arrangement for all of the theme groups.

The final table arrangements, the demonstrated collaborative activity of the scientists in relation to the WITS tool, and the observed need for a large unifying screen for each theme group became the physical and social data of a consolidated model that forms the basis for our concept of a "Science Activity Planner (SAP) Workcenter", discussed in the next section. [5]

The layout used for the final field test is shown on the right side of figure 2. In this arrangement, the tables were also spread out more taking advantage of the width of the room. This arrangement was found to have two additional benefits. We observed more interaction and discussion across the different theme groups as the increased space allowed people to move about more easily. This was especially true between the theme groups on the far left and far right sides of the room, which had been separated from each other in the previous layouts. People also said that they appreciated not having someone seated immediately behind them. The effective capacity of each theme group area in the final configuration was 7, or 9 with two additional chairs placed on the corners of the table. This raised the effective capacity of the operations facility to approximately 50.

Two additional facilities changes were made for the 10-day field test. First, each theme group's WITS workstation was upgraded to have dual monitors, simultaneously providing more screen space and allowing a decrease in the resolution of the monitors, which in effect enlarged the data on the screen. This was very helpful to those scientists seated furthest from the monitors. Second, an additional projection screen was set up in the sandpit behind the operations area that showed a clock and a dynamically updated operations timeline. It was found that this was very helpful in keeping the operations staff aware of schedule constraints.

Several features common to all three layouts were found to have significant benefits. First, even though a second room of similar size was available, the decision was made to fit the complete operations team in one room. While this did result in some crowding, it quickly became apparent that separating parts of the operations staff would have had very negative consequences due to decreased communication. At one point, it was also considered that the second room could be used for the large "SOWG meeting" which occurred during the planning process for each sol. This was the approach used by the Mars Pathfinder mission. However, by having the SOWG meeting in the same room as the theme group areas, several benefits were derived:

1. Limited funds were available for computers and projection equipment, and this arrangement allowed a single set of computers and projectors to be used throughout the operations process.
2. The scientists built their candidate science activities using their WITS workstations and a variety of large printed data products (maps, image panoramas, etc). All of this material was in their theme group area, if they had been required to go to a different room for the SOWG meeting, they would have had to carry much of this material between the rooms.
3. Using the science work area for the SOWG meeting room allowed the SOWG to transition between operations phases very quickly. The SOWG chair merely had to get the attention of the SOWG and announce that a meeting was beginning. When the meeting concluded, people could immediately return to work. This saved time and resulted in a more efficient operations process.

Many other lessons were learned from the FIDO field tests, and are summarized and applied in the next section to develop a new science operations center design. The design is built primarily to fit the needs and limitations of the Mars Exploration Rover Mission, but could be adapted for other missions as well.

4. Facilities Concepts for the 2003 Mission

The lessons learned in the construction and use of the FIDO field test operations center and past Mars mission science operations centers are summarized below:

1. Modern mission operations are almost completely focused on collaborative activities around computers. Operations facilities must be designed to allow large numbers of people to gather around the mission workstations.
2. Whenever possible, long narrow table configurations should be avoided because they are not conducive to discussion and collaboration, especially in a noisy room.
3. Projectors should be used whenever possible to produce large computer displays, eliminating the need for all collaborators to be situated near the computer's monitors.
4. In general, large open rooms are superior to separate offices because they facilitate discussion and interaction among the operations team. Steps must be taken, however, to control noise in these environments.
5. Whenever feasible, meetings should be held in the same room used for the primary science operations work.
6. Power and network connections should be readily available at every table in the science operations center. If possible, raised flooring should be installed to make this convenient and safe.
7. If possible, steps should be taken to control the noise in the science work area.
8. High ceilings in the operations center allow projection screens to be elevated, greatly increasing their visibility.

Proposed Facilities Layout for the 2003 Mission

The 2003 Mars Exploration Rover mission operations centers will be situated on 4 floors of JPL's building 264, with 2 floors devoted to the operation of each rover. The fact that each rover's operations team is divided across two floors provides some significant challenges that are beyond the scope of this paper.

Each floor in building 264 has an immovable central column that contains staircases, elevators, and bathrooms. This column limits one dimension of any room to 36 feet. This limitation represents the most difficult challenge for the design of the MER science operations facility because long, rectangular rooms make it very difficult for a large number of people to see a common projection screen. The science operations staff for the MER mission have identified the need for 3 large rooms for the following functions in the daily operations process:

1. The "Science Work Area", where the science theme groups are located. The scientists use this space each sol to analyze the data acquired by the rover and construct candidate activities for the next sol. In this room are numerous workstations running the Science Activity Planner (SAP) software, which is an adaptation of WITS (see section 2) for the MER mission.
2. The "Science Assessment Meeting Room", where the SOWG will meet each day to discuss the data acquired on the previous sol and make decisions that will guide the generation of activities by the theme groups.

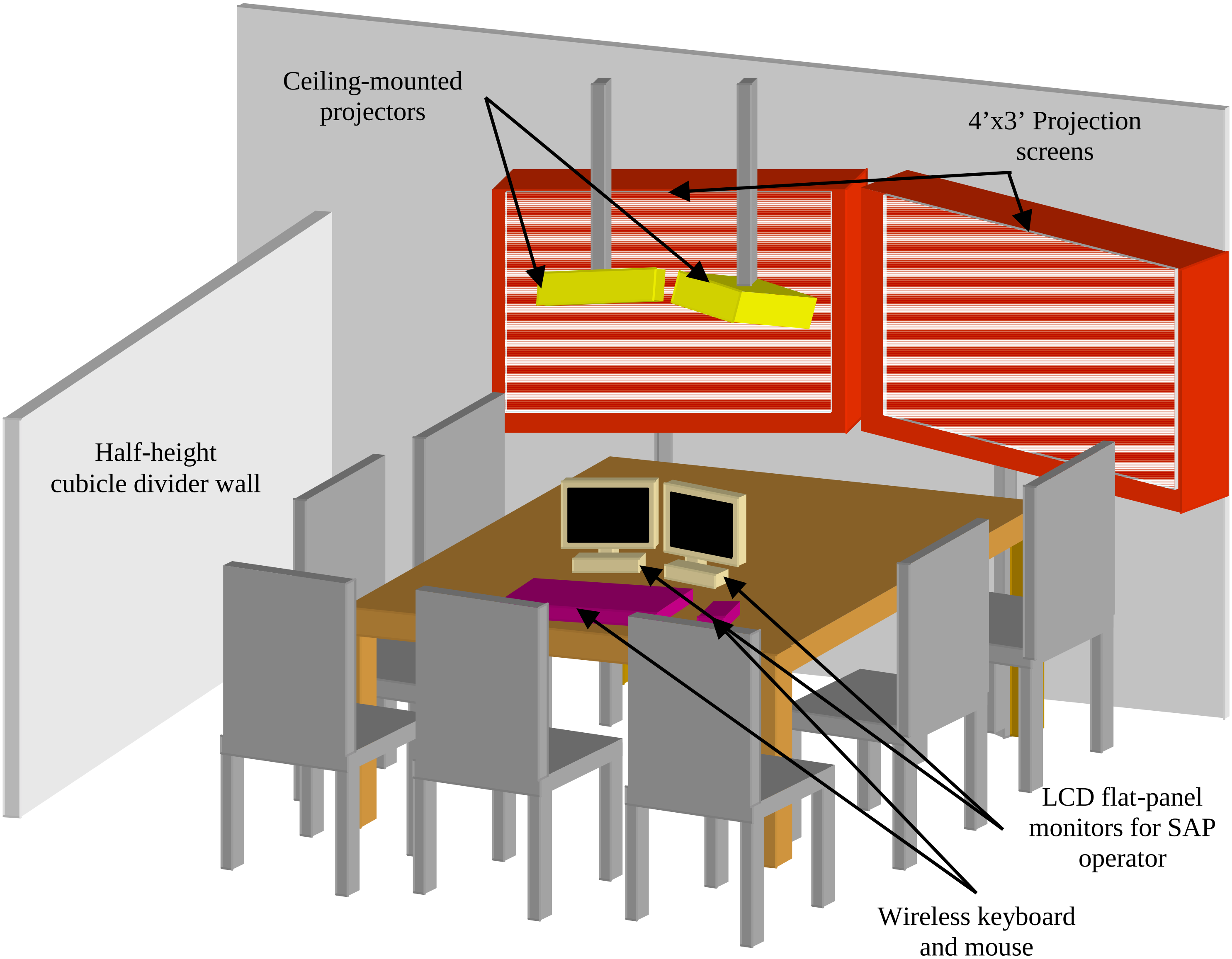

Figure 3: The “SAP Workcenter”, a collaboration environment designed to allow seven scientists to work together using a single SAP workstation.

3. The “Science Operations Working Group Meeting Room”, where the SOWG and additional mission staff will meet daily to build the science activity plan using SAP.

Drawing upon lesson #5 above, the design in this paper attempts to combine these three rooms into one, called the “Science Center” below. This approach has numerous benefits, as enumerated at the end of the last section.

The layout for the Science Center is built around 7 "SAP Workcenters", one of which is shown in figure 3. The SAP Workcenter was designed with lessons 1, 2, 3, and 8 above in mind. Seating is provided for 7 scientists in an arrangement that should facilitate discussion around a large table suitable for holding printed products like maps and image panoramas. The effective capacity of the SAP Workcenter can be increased to 11 by doubling the length of the table. The SAP computer drives two LCD monitors and two ceiling-mounted projectors. The LCD monitors provide the SAP operator with a crisp display for reading small text and discerning fine image details, while the projection screens provide a large display for comfortable viewing by the rest of the scientists. The scientists are all given laser pointers to indicate points of interest on the projection screens. The use of projection screens also allows additional scientists to stand behind the seated scientists temporarily if a larger group needs to discuss a particular piece of data.

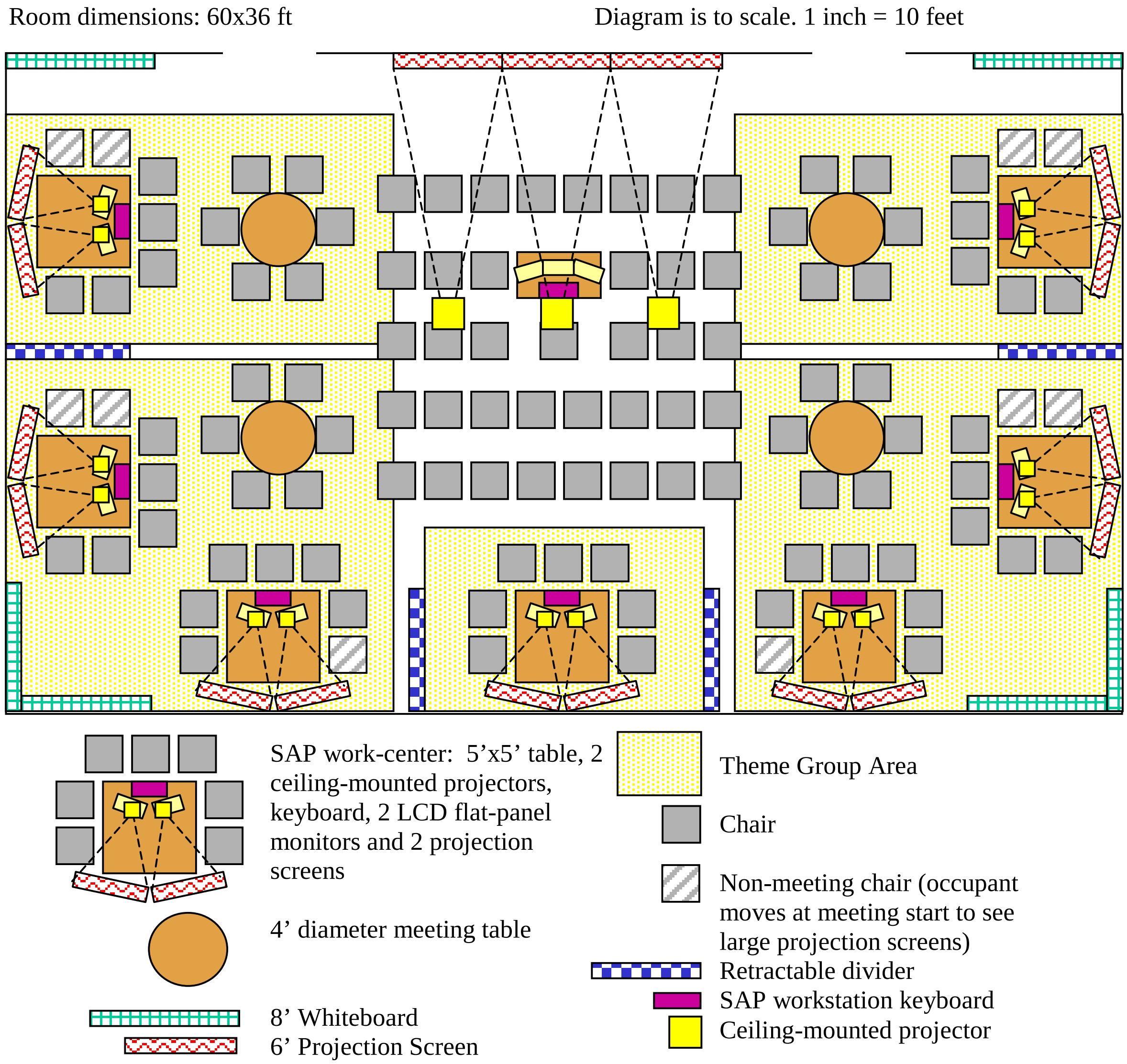

Figure 4: Proposed MER Science Center Layout

The proposed layout for the MER Science Center is shown in figure 4. The space and equipment is divided into six sections as follows:

- One small science theme group area with effective capacity 7, which has a SAP Workcenter, an area for posting printed data products, and easels with large pads of paper.
- Two medium science theme group areas with effective capacities of 13 each, which each have a SAP Workcenter, a 4’ circular meeting table, an area for posting printed data products, and an 8’ whiteboard.
- Two large science theme group areas with effective capacities of 20 each, which each have 2 SAP Workcenters, a 4’ circular meeting table, an area for posting printed data products, and two 8’ whiteboards.
- A central theatre with additional seating for highly attended meetings, situated in front of three large projection screens. In the middle of the theatre is a SAP workstation that drives the three large ceiling-mounted projectors pointed at these screens.

As recommended by lesson #6 above, every table in the Science Center has multiple power and network connections to allow scientists to use their personal laptop computers.

The layout provides seating for 110, comfortably. However, 10 chairs in the room (marked with diagonal lines) cannot see the large projection screens. When a meeting starts, the occupants of these chairs either need to move to another chair or move their chair to a different location. Therefore, the total effective capacity of the room is 100. When the dividers between the STGs are retracted, everyone in this room can comfortably see and hear everyone in the room, see the central projection screens, and contribute to the development of the science activity plan.

There are 4 retractable dividers (7' long and 5' high) between the theme groups that are intended to shield each theme group from some of the noise produced by SAP Workcenters in neighboring theme groups, as was recommended by lesson #7 above. These walls are short enough for people to see and talk over while standing. The room can be converted into a large meeting area by retracting the dividers. To further control noise in the Science Center, the room should be carpeted and acoustic tile should be used in the ceiling.

Note that this room attempts to serve the needs of all three rooms described at the beginning of this section. By combining these functions into one environment, the SOWG would be able to transition between operations phases quickly and convene unscheduled meetings with minimum disruption if the need arose. Another benefit to holding all science meetings in this room is that it would be straightforward to configure the room so that one of the three large screens in front of the central theatre could be temporarily connected to any of the SAP Workcenters. This would allow scientists to prepare a set of SAP views at their Workcenter that illustrates a point they wish to discuss before it is their turn to speak. When their turn came, they could quickly switch one of the large screens to their Workcenter and use it as a visual aide for their comments. When meetings are not in progress, these screens are used to display data of common interest and an operations timeline.

There are some significant drawbacks, however, to this single room approach that should be mentioned. The tables and chairs in this room have been arranged to provide a number of separate, semi-private work areas. This is clearly at odds with the goal of providing a large meeting space. In general, there is a danger that by trying to design a room to satisfy three purposes, it may not satisfy any of these purposes effectively. One reasonable alternative is to use this room as the Science Work Area and Science Assessment Meeting Room, but build an additional room for the Science Operations Working Group Meeting Room that has the single goal of providing a comfortable meeting area for a large number of people.

5. Advanced Concepts for Future Missions

The above examples illustrate how the effective capacity of an operations facility can be greatly increased through careful layout designs. However, there is clearly a limit to the progress that can be made in this area. Further significant advances in Mars mission operations can only be realized through major changes in the technology used for operations. This section is devoted to two operations facility concepts that represent fundamental advances in the state of the art in mission operations.

Full-scale Immersive Operations

Workstation-based immersive 3d graphics have already been applied to past Mars missions with great success. Devices such as LCD shutter glasses increase the immersive effect, but only for a small number of people. It is a central theme of this paper that surface mission operations demands extensive collaboration between operations staff members using the operations computers. One way to enable a large number of people to interact in an immersive environment is to use large-scale interfaces, often called "CAVEs" (CAVE Automatic Virtual Environments). An example of a CAVE is shown in figure 5.

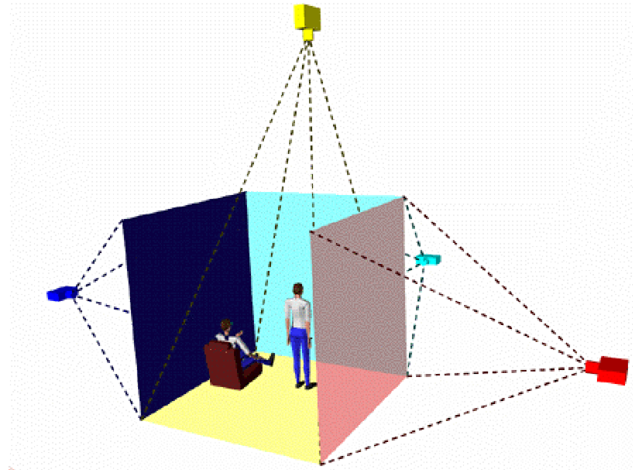

Figure 5: An example of a CAVE. [6]

It is fairly straightforward to display Martian terrain in a CAVE, but several challenges must be addressed before this technology can form the basis of a useful mission operations environment. Foremost among these challenges is the development of a useful input interface. Since numerous scientists need to be able to simultaneously interact with the display (creating targets, building activities, etc.), a client/server based system is required. One approach would be to setup several computers inside the environment. However, this would damage the immersive nature of the environment, and would greatly limit the motion of the scientists.

A more appropriate input interface would be based on a handheld personal digital assistant (PDA). A PDA with wireless Ethernet or Bluetooth networking is less expensive than a complete computer system, and would allow a scientist to move freely within the virtual environment. A networked PDA would have the additional benefit of serving as a common link between all of the operations participants, allowing one scientist to page another scientist by sending a message to his PDA, for instance. To better illustrate how a PDA could be used as an operations interface, an example of how a scientist might use such an interface is described below.

A scientist arrives at the operations center and selects a PDA from a charging farm. It asks him for a username and password, which informs a central server of the identity of the person currently using that particular PDA. The scientist enters one of the CAVEs showing the latest telemetry. The CAVE shows a panoramic 3D display of the terrain near the rover, with 2D data plots hovering over locations where scientific data has been acquired. After reviewing some of the data, he decides he would like to create a target on a particular rock and describe it. Above the screen he is looking at is the number “4”. He enters this number into his PDA, informing the device that his requests should affect that particular display. He then selects an option on his PDA that creates a pointer on the large display in front of him, and uses the PDA controls to maneuver that pointer to the rock he is interested in. When he is satisfied with the pointer’s location, he presses a button on his PDA and an interface is displayed *on the PDA* for describing the target. He labels it, provides a brief textual annotation, and saves it. It is immediately stored in a central server and is accessible by all other mission scientists. He builds proposed activities in a similar fashion, with the activity editing interface displayed on his PDA.

By making the PDA responsible for rendering the operations input interface, this approach allows the CAVE to function entirely as an output and visualization device. It also enables a large number of users to interact with the same CAVE because each user’s input interface is rendered on their PDA instead of on the large screens, where they would cover up terrain and interfere with other users’ work. Research is currently being done into technologies that will make this system possible.

Distributed Operations

This paper has focused primarily on designs for large-scale, centralized operations facilities. In general, the goal of a centralized operations facility is to concentrate everything in as small of an area as possible in order to improve communication among the members of the operations team. However, numerous technological advances have provided future missions with an alternative. Distributed operations allow significant portions of the operations staff to participate in the mission from outside the mission operations center. The benefits of distributed operations are many. A few are described below.

1. *Reduction in Operations Costs* - Scientists participating in the mission from their home institution can make use of their own equipment and office space. The mission can also avoid considerable travel expenses, including airfare, hotel accommodations, rental cars, and living expenses for hundreds of scientists for the duration of the mission and the tests leading up to it.

2. *Convenience for Mission Personnel* - Currently, anyone wishing to participate in a JPL surface mission must be willing to effectively move to Pasadena, California for many months. Many of scientists have families and careers that make it very difficult to make this commitment, and may not be comfortable spending so much time traveling to and from JPL. Potentially, this could discourage some of the best scientists from participating, which is ultimately a loss for the mission. As missions lengthen in duration, these considerations will continue to increase in importance.

3. *Less Disruption to Other Projects at JPL* - It was mentioned above that the MER mission will be using 4 floors of a JPL building for operations. Obviously, these floors are not currently vacant. This means that all of the occupants of these floors (hundreds of people) must be permanently relocated to other offices so that renovations can take place and the mission operations personnel can be moved in. At the conclusion of the mission, the mission operations personnel will have to be moved back out of this building so that further renovations can take place to reestablish suitable office space. In addition to the obvious costs to the MER mission, many other projects will be disrupted as a result of these changes.

4. *Vastly Increased Effective Capacity* – Distributed operations allows a mission to draw upon the expertise of an enormous number of scientists and engineers. Clearly, the principal challenge for a distributed operations system is meeting the conditions presented in the introduction for *meaningfully* engaging these distributed participants in the operations process.

Distributed operations is gradually becoming a part of mission operations at JPL. The Mars Polar Lander mission was to have been the first mission to allow remote scientists to participate in operations over the Internet. [7] The Web Interface for Telescience (WITS) and the Multi-mission Encrypted Communication System (MECS) were designed to enable scientists and engineers to participate in the mission equally whether they were inside or outside the mission operations center. [8] Even though MPL did not reach the surface of Mars safely, it should be noted that WITS was successfully used in the Operational Readiness Tests leading up to landing, and allowed scientists at the University of Arizona and engineers at JPL to participate in these tests remotely. WITS has also been used numerous times in the FIDO field tests to enable remote scientists and engineers to participate in, and even lead field exercises from their home institutions.

The MER mission will make use of the distributed operations capabilities of The Science Activity Planner (SAP), the successor of WITS. Using SAP, participating scientists at universities around the country will be able to access mission data, review plans created in the operations center, and participate in discussions with the team in the operations center as part of the “Extended SOWG”.

Finally, the 2009 Mars mission, just entering its design phase, is likely to depend heavily on distributed operations. Since this mission’s rover may operate for as long as 2 years, many consider distributed operations a necessity for mission success.

6. CONCLUSIONS

A properly designed operations center is vital to the success of a mission. A variety of operations facilities designs, ranging from historical approaches to more advanced concepts were discussed in this paper. While the examples presented were primarily focused on the particular requirements of JPL's Mars missions, many of the lessons and designs discussed may be applicable in other contexts. For instance, since the proposed layouts for the MER mission are built around multiple SAP Workcenters, the design should scale well to larger and smaller applications. In addition, refinements to the designs in this paper may be possible by drawing on the related field of military "situation room" design.

ACKNOWLEDGEMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] Springer, T.J. Does ergonomics make good business sense? Facilities Design and Management, 11, 46-49. 1992.

[2] Hall, E.T. The Hidden Dimension (1st ed.). Garden City, NY: Doubleday. 1966.

[3] E. T. Baumgartner, "In-Situ Exploration of Mars using Rovers," Proceedings of the AIAA Space 2000 Conference, AIAA Paper# 2000-5062, Long Beach, CA, September 2000.

[4] Suchman, L.A. Plans and situated actions-The problems of human-machine communication. New York: Cambridge University Press. 1987.

[5] Beyer, H., Holtzblatt, K. Contextual design-Defining Customer-Centered Systems. San Francisco: Morgan Kaufmann Publishers. 1998.

[6] University of Michigan Virtual Reality Laboratory Webpage. http://www-vrl.umich.edu/intro/.

[7] Paul G. Backes, Kam S. Tso, Jeffrey S. Norris, Gregory K. Tharp, Jeffrey T. Slostad, Robert G. Bonitz, and Khaled S. Ali. Internet-based operations for the mars polar lander mission. In Proceedings IEEE International Conference on Robotics and Automation, pages 2025–2032, San Francisco, California, April 2000.

[8] Jeffrey S. Norris and Paul G. Backes. Wedds: The wits encrypted data delivery system. Proceedings IEEE Aerospace Conference, Big Sky, Montana, March 2000.

Jeff Norris *is a computer scientist and member of the technical staff of the Autonomy and Control Section at the Jet Propulsion Laboratory. At JPL, his work is focused in the areas of distributed operations for Mars rovers and landers, secure data distribution, and science data visualization. Jeff is a member of the ground data systems team for the 2003 Mars Exploration Rover Mission, and is responsible for the design and development of part of the rover activity planning software suite. He received his Bachelor's and Master's degrees in Electrical Engineering and Computer Science from MIT. While an undergraduate, he worked at the MIT Media Laboratory on data visualization and media transport protocols. He completed his Master's thesis on face detection and recognition at the MIT Artificial Intelligence Laboratory. He lives with his wife, Kamala, in La Crescenta, California.*

Roxana Wales *has been research scientist doing work practice studies to support technology development with the Work System Design and Evaluation Group at the NASA Ames Research Center in Mountain View, CA. for three years. She has a Ph.D in cultural psychology from the California Institute of Integral Studies. At NASA she has worked on technology development projects for both the Shuttle and the International Space Station at Johnson Space Center and has done a study of airline and airport operations to support the development of aeronautical technology. Before coming to NASA, she was a work practice consultant in Silicon Valley and with Xerox PARC.*

Mark Powell *is a member of the technical staff in the Autonomy and Control Section at the Jet Propulsion Laboratory, Pasadena, CA since 2001. He received his B.S.C.S. in 1992, M.S.C.S in 1997, and Ph.D. in Computer Science and Engineering in 2000 from the University of South Florida, Tampa. His dissertation work was in the area of advanced illumination modeling, color and range image processing applied to robotics and medical imaging. At JPL his area of focus is science data visualization and science planning for telerobotics. He is currently serving as a software and systems engineer, contributing to the development of science planning software for the 2003 Mars Exploration Rovers and the JPL Mars Technology Program Field Integrated Design and Operations (FIDO) rover task. He, his wife Nina, and daughters Gwendolyn and Jacquelyn live in Pasadena, CA.*

Paul Backes *is a technical group leader in the Automomy and Control section at the Jet Propulsion Laboratory, Pasadena, CA, where he has been since 1987. He received the BSME degree from U.C. Berkeley in 1982, and MSME in 1984 and Ph.D. in 1987 in Mechanical Engineering from Purdue University. He is currently responsible for distributed operations research for Mars lander and rover missions at JPL. Dr. Backes received the 1993 NASA Exceptional Engineering Achievement Medal for his contributions to space telerobotics (one of thirteen throughout NASA), 1993 Space Station Award of Merit, Best*

Paper Award at the 1994 World Automation Congress, 1995 JPL Technology and Applications Program Exceptional Service Award, 1998 JPL Award for Excellence and 1998 Sole Runner-up NASA Software of the Year Award. He has served as an Associate Editor of the IEEE Robotics and Automation Society Magazine.

Robert Steinke *is a computer scientist and member of the technical staff of the Autonomy and Control Section at the Jet Propulsion Laboratory. At JPL, his work is focused in the areas of distributed operations for Mars rovers and landers, secure data distribution, distributed data consistency, and communication support for group collaboration. He received his B.S. in 1995 and M.S in 1997 in Computer Science from U.C. Santa Barbara, and his Ph.D. in 2001 in Computer Science from the University of Colorado at Boulder. As a graduate student he completed his Master's thesis on a serializable lazy update scheme for distributed databases, and his dissertation on distributed shared memory consistency models, and received a graduate teacher certificate from Boulder for his training and work as an instructor. He now lives in Pasadena with his wife Mollie and daughter Adelaide.*